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Development of a Sampler for Particulate-Associated and Low Volatility Organic Pollutants in Residential Air

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DEVELOPMENT OF A SAMPLER FOR PARTICULATE-ASSOCIATED AND LOW VOLATILITY ORGANIC POLLUTANTS IN RESIDENTIAL AIR

by

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This report describes the development of a sampler for particulate-associated and low volatility organic pollutants in residential air. The performance of the sampler inlet, which is compatible with the proposed PM-10 regulations for particulate sampling, is documented under a variety of conditions of interest. The details of construction of the sampler and the resulting acoustic performance of the unit are described. While the unit described in this report is capable of performing the task for which it has been designed, several design enhancements are recommended which would result in an improved residential air sampler.

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FOREWORD

Only limited information is currently available on the quality of indoor air. Since most of the population spends a major part of each day indoors, the indoor air quality may be a more important component of the risk to which the public is subjected than is the outdoor air quality. Recent trends towards energy-efficient building construction typically result in significant reductions in the indoor-outdoor air exchange rate. This fact, coupled with the increasing use of alternative heating sources in homes, results in a potential for concentrations of incomplete combustion products to reach undesirable levels.

Current analytical techniques for these organic compounds require sampling of large volumes of air with a filter/sorbent combination. The use of available ambient high volume air samplers in occupied residences is not practicable due to the noise they emit and the very high flow rates they employ. There was a need to develop an air sampler suitable for in-house usage so that the quality of indoor air can be adequately assessed. This report describes the initial development of such a device.

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ABSTRACT

This report describes the development of a sampler for particulate-associated and low volatility organic pollutants in residential air. The performance of the sampler inlet, which is compatible with the proposed PM-10 regulations for particulate sampling, is documented under a variety of conditions of interest. The details of construction of the sampler and the resulting acoustic performance of the unit are described. While the unit described in this report is capable of performing the task for which it has been designed, several design enhancements are recommended which would result in an improved residential air sampler.

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SECTION 1

INTRODUCTION

Until recently, research and monitoring efforts have generally focused on assessing and improving the quality of air in the ambient (outdoor) environment. However, concern has become more pronounced regarding the effects of indoor air quality on the public welfare. Some reasons prompting this concern are recent studies[1,2] demonstrating the variety of pollutants that are emitted from commercial products used indoors, the increase in woodburning as a heating source, and the "tightening", that is, reducing the air exchange rate, of buildings as an energy conservation measure. Contributions of indoor pollutants to total exposure can be much greater than those of outdoor pollutants.

For many organic compounds of interest, methodology has not been readily available to determine airborne pollutant levels in indoor environments. Because some of these compounds pose a health risk at very low concentrations, there is the need to sample air at the highest practicable rate in order to collect sufficient material for analysis. Either the sampling rate of existing systems does not provide adequate sample mass for detection at levels prevalent in indoor air, appropriate equipment is not available, or existing samplers (usually ambient types) are not suitable for indoor applications because of size, noise, etc.

In this project an air sampler was developed for indoor use that can collect quantities of particulate-bound and vapor phase organic compounds sufficient for detailed organic analysis and biological screening. The particulate and vapor phase samples of the semi-volatile compounds are collected by the sampler in a manner intended to minimize artifact formation and background interferences that would be detrimental to the subsequent analyses and bioassays. Sample analyses to verify that this objective was achieved were not performed as part of this project. The inlet provided for the system is designed with a nominal 10 μm cut

point consistent with proposed requirements for PM-10 ambient particulate samplers. The resulting sampler is quiet, transportable, and relatively unobtrusive. Its low maintenance requirements and high reliability are additional factors which render it suitable for air sampling in residential environments.

SECTION 2

CONCLUSIONS

A high volume air sampling system suitable for use in residential environments has been developed and evaluated. The flow rate achievable with this device is adequate for at least eight hour time resolution of typical concentrations of most semi-volatile organics of interest in either the particulate or the vapor phase. The system is quiet, transportable, and relatively unobtrusive.

Results obtained during building and testing the prototype air sampler can be summarized as follows:

- PM-10 Inlet -- The inlet for aerosol particles achieves a cut point of 10 μm aerodynamic diameter and is reasonably insensitive to small variations in the sampling flow rate. Carryover of large particles and particle bounce have been essentially eliminated in the inlet.

- Sorbent Bed -- The sampler is capable of collecting adequate samples on the sorbent bed for limited time resolution of the species of interest at the design flow rate.

- Acoustic Goal -- A noise criterion (NC) of NC = 45 was achieved versus the stringent design goal of NC = 35. A few minor design changes to eliminate a spurious whistle and increase the baffling in the motor cooling chamber should permit reaching NC = 37.

- Motor Cooling -- The motor cooling air must be carefully separated from the hot vacuum exhaust air in order to prevent air recirculation and subsequent overheating of the motor.

Overall the prototype has proven the basic design to be effective. The design goals can be met with minor redesign, and limited additional testing would be required to confirm the effectiveness of the modifications.

SECTION 3

RECOMMENDATIONS

Based on the results of this study, the following modifications of the sampler are recommended:

- Ancillary Equipment -- The sampler should be equipped with a continuously recording flow rate monitor and with an elapsed time indicator.

- Acoustics -- The source of a spurious whistle during operation of the current sampler should be located and eliminated. This would permit achievement of NC = 40, at least.

- Safety -- A simple fire alarm system should be installed to detect high temperature or smoke and shut off the electric supply.

- Motor Isolation -- The motor mounting should be redesigned as shown in Figure 1.

- Portability -- The current design has the aluminum sampling head screwed to the motor enclosure. The entire package is too tall for convenient transport. If the sampler could be removed from the enclosure with a simple quick release mechanism, the system would be much easier to transport.

- Plywood Shell -- The Pliobond adhesive, because it is solvent-based, was unsatisfactory -- warpage separated the two 1/2-inch sheets. Either a different adhesive or 1-inch plywood panel is recommended.

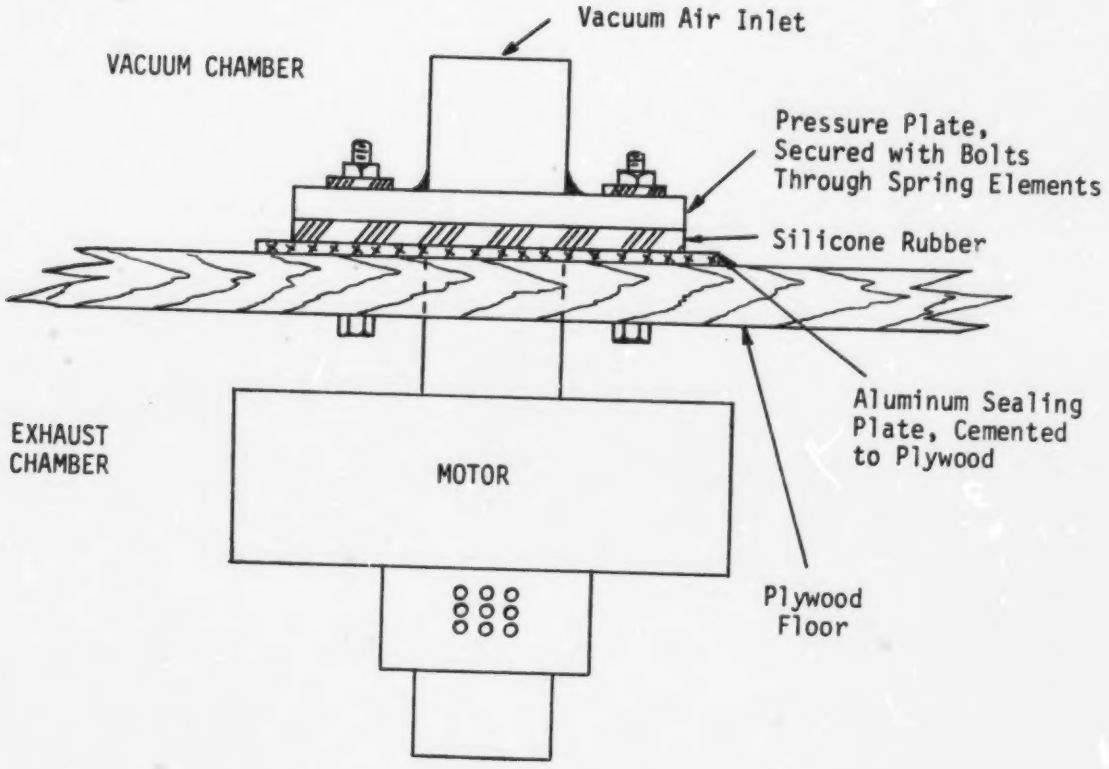


FIGURE 1. SUGGESTED MOTOR ISOLATION MOUNT DESIGN

SECTION 4

PROCEDURES

A general description of the components of the indoor air sampler and a discussion of the considerations that established the design criteria for the system are given below.

SAMPLER COMPONENTS

The indoor sampler design is patterned after the ambient unit described by Lewis, et al.[3] The basic components of the system are illustrated schematically in Figure 2 and photographs of the device are contained in Figure 3. The inlet has been designed to provide for size discrimination of particles based on PM-10 criteria for ambient monitors. The sampling module is similar to that developed by Lewis and Jackson[4]. This sampling module has been used in a pilot study of residential air performed in the winter of 1984 and found to be effective in collection of adequate samples for both chemical analysis and bioassay[5-7]. Quartz fiber appears to be the best filter material for collection of particulate material to meet the proposed PM-10 standard[8]. Other substrates, such as Teflon-coated Pallflex, can be used in place of the more brittle quartz and may be more suitable for samples when bioassay is of primary importance. As discussed below, the system has been designed so that both polyurethane foam (PUF) and a sorbent bed, for example XAD-2, can be used for collection of semivolatile organic compounds.

Selection of a suitable air mover is a critical aspect of the design since a high sampling rate is desired, yet the noise level, size, and power requirements of the pump or blower are required to be such that the system will be unobtrusive when employed for indoor sampling.

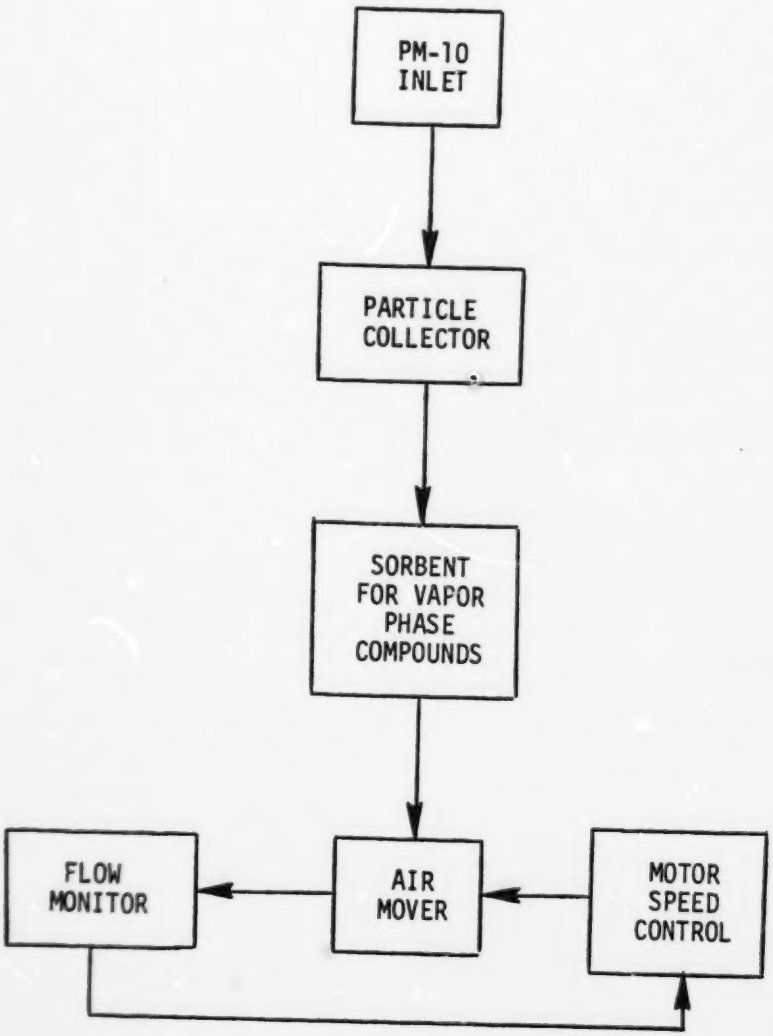
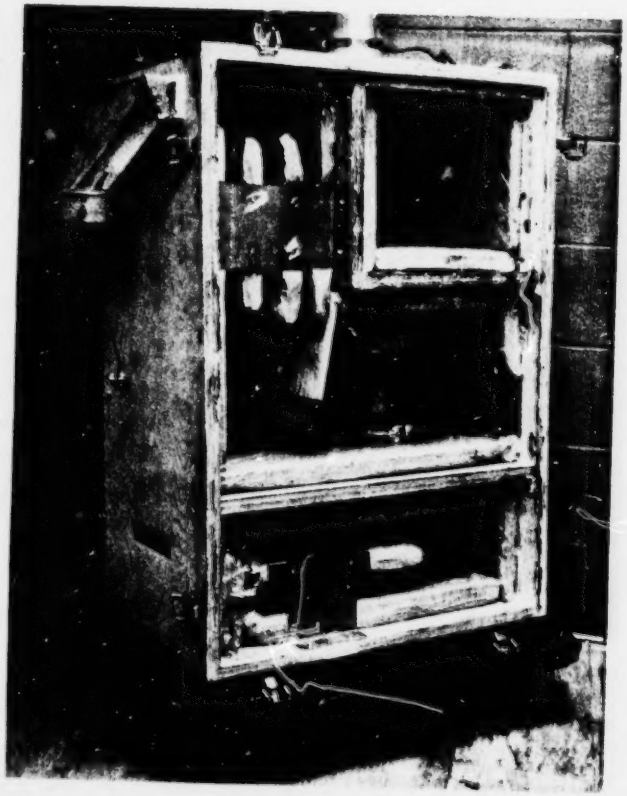
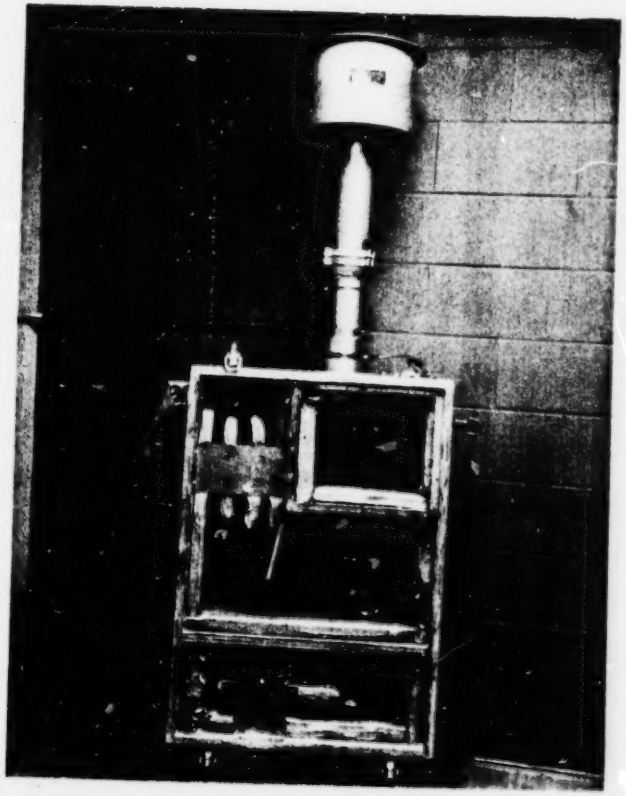


FIGURE 2. SCHEMATIC DIAGRAM OF COMPONENTS OF INDOOR AIR SAMPLER



(A)



(B)

FIGURE 3. (A) VACUUM MOTOR ACOUSTIC ENCLOSURE
(B) ENCLOSURE WITH PM-10 INLET

An additional component of the sampler is a motor speed control to adjust the sampling rate, since different media will impose different loads on the blower, resulting in undesirable uncertainties in sampling flow rate.

FLOW RATE REQUIREMENTS

The flow rate requirements for the indoor sampling system are determined primarily by the quantity of material needed for organic chemical analysis and/or bioassays. The system must collect sufficient sample so that organic pollutant levels prevalent in indoor air may be determined by chemical analysis [gas chromatography (GC), combined gas chromatography/mass spectrometry (GC/MS), or high performance liquid chromatography (HPLC)] and so that definitive results may be obtained from biological screening. In addition, collection of an adequate-sized sample should be achieved over a time interval that permits resolution of pollutant levels originating from specific sources or activities such as cooking or fireplace use in a residence. On one hand, these requirements dictate that the sampling rate, especially for collection of samples for biological testing, be as high as possible. On the other hand, considerations such as noise level, size of the sampler, and effects on air exchange require a compromise in the sampler flow rate. The latter consideration is important since the sampling could affect the natural air flow between the outside and inside of a residence and between rooms within the dwelling, if the exhaust is vented in a different location from collection.

The data shown in Table 1 indicate our best estimate of the quantification levels for various low volatility organic compounds of potential interest. These values represent the low end of concentrations observed in various indoor air studies reported in the literature. A minimum time resolution value has been calculated using an assumed sampling rate of 8 cfm.

As shown in Table 1, PAH and dioxin sampling requirements are much more demanding than pesticide and PCB requirements. However, assuming a desired time resolution of eight hours, all of the compounds can be determined, except dioxin, using the instrumental techniques designated in the table. With the exception of dioxin, a 4 cfm sampling rate would be sufficient to provide eight-hour time

TABLE 1. ESTIMATED SAMPLING REQUIREMENTS FOR SELECTED SEMIVOLATILE COMPOUNDS

Compound	Estimated Concentration in Indoor Air, ng/m^3(a)	Estimated Quantification Level, ng/Sample(b)	Required Sampling Time at 8 cfm, minutes
PAHs (GC/MS)			
Phenanthrene	5	50	45
Pyrene	2	50	110
Chrysene	1.5	20	60
Benzo(a)pyrene	0.5	20	180
Benzo(g,h,i)Perylene	1.0	20	90
Coronene	0.5	20	180
1-Nitropyrene	0.1	5	220
Dioxin (2,3,7,8-TCDD)(c)	0.001	0.2	890
PCBs (GC/ECD)	10	200	90
Pesticides (GC/ECD)			
Chlordane	100	200	10
Dichlorvos	50	20	2
Malathion	100	40	2
Ronnel	10	40	18

(a) Estimates based on the lower limit of levels reported in the literature. These have been selected as detection limits to be achieved using the sampler developed in this program.

(b) Quantification level is 3 to 4 times the instrumental detection limit.

(c) Indoor air data not available. Unpublished ambient air data used for this estimate.

resolution. A higher flow rate could yield time resolution over even shorter intervals.

Thus, a sampling flow rate of 8-10 cfm appears to be a reasonable upper bound from the standpoint of analytical requirements, and this limit does not present serious practical difficulties. This flow rate will permit collection of sufficient sample for chemical analysis of most organic compounds with adequate time resolution. Collection of sufficient samples for biological screening may require longer sampling intervals, which would result in decreased time resolution.

SAMPLING EFFICIENCY, ARTIFACT FORMATION AND BACKGROUND INTERFERENCE

In selection of sampler construction materials and sampling media, sampling efficiency, artifact formation, and potential background interferences are all important criteria. One of the most important considerations is the type of adsorbent to be employed for collection of semivolatile organic compounds. Polyurethane foam has been found to be satisfactory for collection of a wide range of compounds for organic chemical analysis.[9] The material has a relatively low pressure drop, provides efficient collection, and does not present any severe artifact formation or background interference problems for the chemist.

Polyurethane foam has been reported to produce mutagenic artifacts, although recent work indicates this may not be the case with appropriate cleanup procedures[7,10]. Thus PUF may not be appropriate for collection of samples for biological screening. A sorbent, such as XAD-2, may be preferable for use when the indoor sampler is used to collect samples for biological testing. For this reason, the sampler has been designed to accommodate both PUF cartridges and a sorbent bed to enable it to fulfill the sample requirements for both chemical and biological analyses. A high-purity quartz fiber filter precedes the adsorbent cartridge or bed to collect particulate material. The quartz fiber material has a high collection efficiency, low pressure drop, and minimal background interferences.

Construction materials used in the sampler have been selected so that sample integrity is not compromised. Probably the most important consideration in this

respect is the gasket material used to seal the filter and PUF cartridge or adsorbent bed.

PM-10 INLET

The sampler inlet accommodates a flow rate of 8.5 cfm and is designed to fractionate indoor aerosol with a cut point of 10 μm. The performance characteristics of the fractionator are intended to be in accordance with the appropriate suggestions of EPA for outdoor samplers.[11]

Air is drawn into the inlet shown in Figure 4 and then into the first stage fractionator, which consists of a set of six acceleration jets, each 18.0 mm diameter, where the larger particles are removed from the distribution. The air is then passed through the second fractionation stage, which is also composed of a set of six acceleration jets of the same size as those in the first stage, where additional noninhalable aerosol is stripped from the distribution. This second stage minimizes the probability of "pass through" of large particles due to bounce. Through the mechanisms of inertial impaction, turbulent deposition, and gravitational settling, large particles are deposited within the inlet. The stream containing inhalable aerosol flows through a vent jet, 62.7 mm in diameter, and then through to the filter.

NOISE

In order to assure that the sampler would be acceptable for indoor use from the standpoint of noise, a noise control task was included in the design effort. The noise control objective was to make the sampler satisfactory for use in bedrooms. Consequently, a noise level consistent with a Noise Criterion value of 35[12] was selected in the noise control design. Noise Criteria (NC) is an application based guide to an acceptable noise level. The NC is a dimensionless number which applies to steady, continuous spectrum, broad-band noise. NC-35 was recommended as a design goal for this sampler by Battelle, since that value is typical of the maximum acceptable background noise of a residential sleeping room.

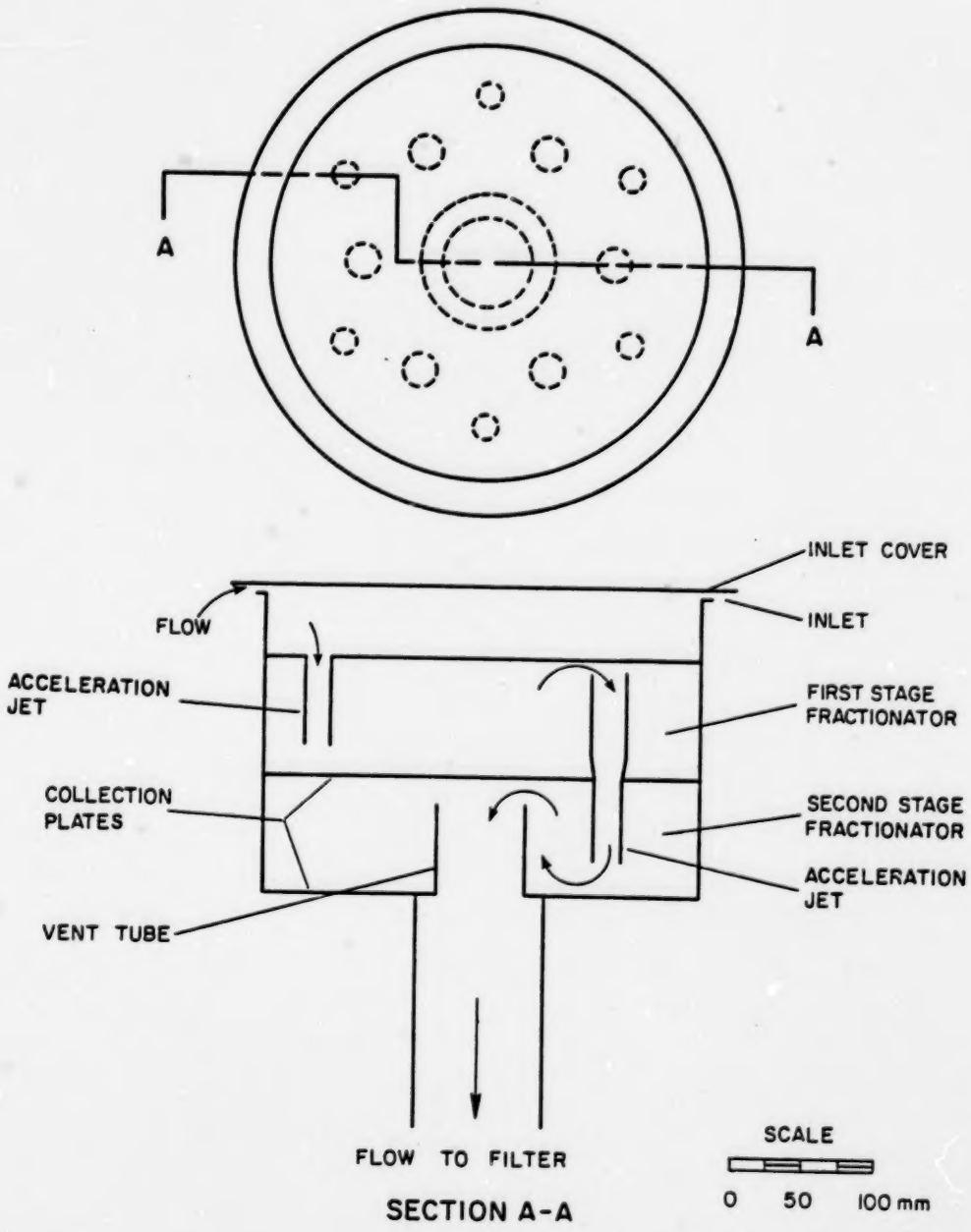


FIGURE 4. PM-10 TWO-STAGE INDOOR AIR SAMPLING INLET

The design of the motor enclosure was dictated by requirements for acoustic isolation in order that the sampler may be used unobtrusively in a home, adequate motor cooling to provide acceptable motor life, and chemically inert construction materials so that outgassing from construction materials used in the sampler does not alter the environment being measured.

Acoustic Isolation of the Motor

An initial step in the acoustic design was to characterize the motor (Amtex by-pass vacuum motor 116100-00 available from Ametek, Lamb Electric Div., 627 Lake Street, Kent OH 44240) as a noise source to determine the amount of attenuation needed as well as the noise frequencies that would require special treatment because of their dominance.

Figure 5 shows the results from a study of the motor, using a sound level meter at the various inlets and outlets to characterize the sound spectrum. Inlet D indicated on the figure radiates noise into the vacuum chamber. Positions B and C radiate into the enclosure exhaust chamber. Inlet A radiates noise into the motor cooling air inlet chamber.

An estimate of the attenuation that might be expected (per linear foot of duct) was done in order to determine what duct length would be needed, given a box width of 18 inches. The estimate was done using the expression[13]

$$A = 12.6 \frac{P}{S} \alpha^{1.4}$$

where

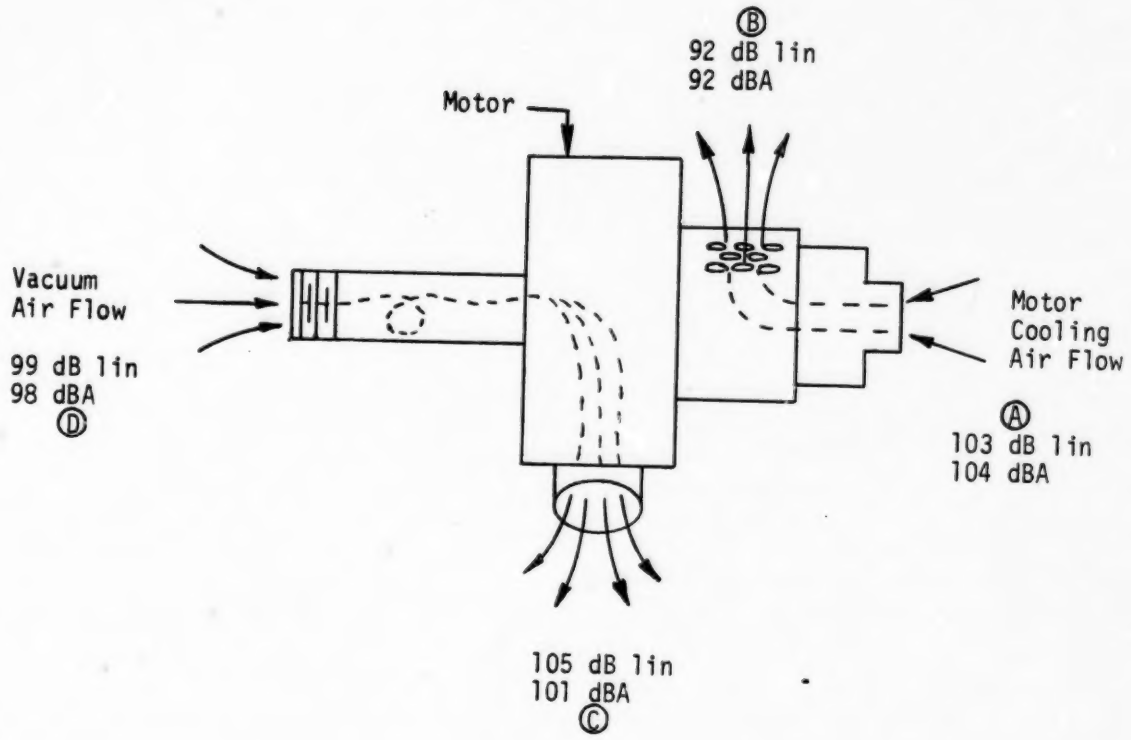
A = attenuation, dB/ft

P = perimeter of duct, in

S = duct open cross section, in^2

α = absorption coefficient for duct liner material at each octave band center frequency.

The absorption coefficients used were for one-inch glass fiber and yielded attenuations of 46, 49, and 48 dB/ft at respective octave band center frequencies of 1000, 2000, and 4000 Hz.



Position	Octave Band Center Frequency, Hz									
	32	63	125	250	500	1000	2000	4000	8000	16000
A	65	67	73	80	86	85	92	100	89	75
B	74	73	74	78	83	87	88	89	80	70
C	89	94	97	99	93	93	97	97	90	82
D	65	67	76	83	88	91	90	90	84	78

FIGURE 5. SOUND PRESSURE LEVELS AT VARIOUS MOTOR INLETS AND OUTLETS (Linear dB)

It was estimated then that 12 inches of duct in conjunction with a lined plenum would be sufficient for the motor cooling air inlet chamber as well as the combined exhaust chamber. The vacuum air inlet was designed with just the plenum chamber since the PUF filtering system and PM-10 inlet act somewhat as mufflers.

The material selected for lining the plenum chambers was two-inch semi-rigid glass fiber board. This material is a packed fiberglass material available at most building supply houses. The semi-rigid board can be readily cut to the shapes needed for the box interior. Various methods of covering the glass fiber panels were investigated such as plastic film, glass mat facing, and an elastomeric coating. The coatings are only needed for pieces of glass board that will be handled often. Release of glass fibers into the air flow should not degrade the fiber surfaces because the semi-rigid board has bonded fibers. Mechanical damage from handling is more likely to be a concern. The heat-shrinkable plastic film (<.005 in) selected for use was the least detrimental to the acoustic properties and was easily applied.

A final point concerning isolation of the motor is the design of the vibration isolation mounting. The motor is suspended by its vacuum inlet pipe. A flange attached to the pipe rests on a soft silicone rubber pad on the floor of the vacuum air inlet chamber. With this arrangement, the motor swings freely through a hole in the plywood support -- completely vibration-isolated from the box. This scheme can be seen in Figure 6. The glass fiber tube at the motor cooling air inlet adequately restrains the motor without defeating the vibration isolation.

Motor Cooling

Because the motor requires cooling air supplied independently of the sampler exhaust, provision had to be made to provide silencing of the cooling air path. Figure 6 shows the two air flow paths for the motor. The vacuum air enters from above (through the sampler) and is exhausted horizontally through the tangential nozzle. It is essential that the vacuum air and motor cooling air be separated to prevent overheating of the motor due to air recirculation. However both

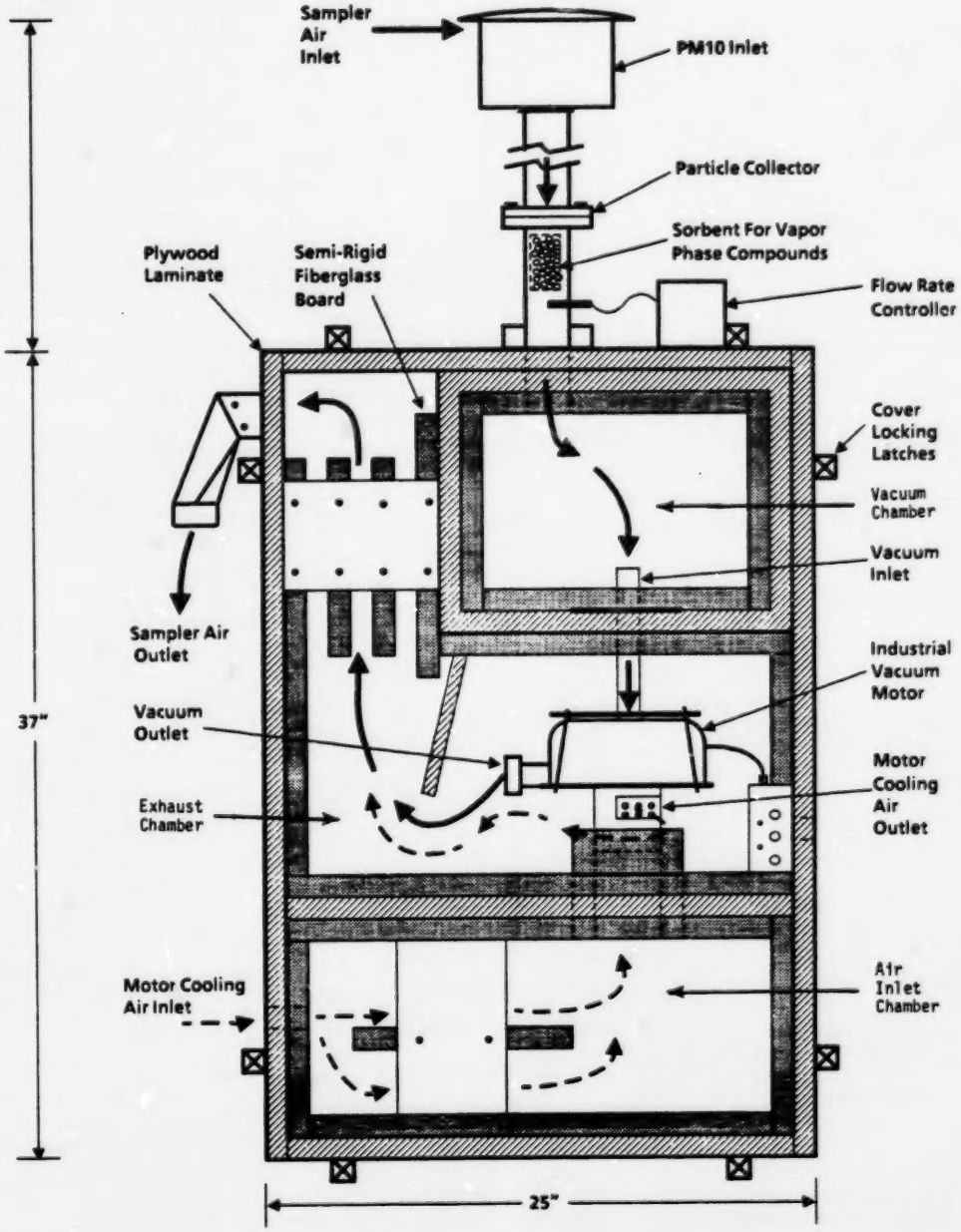


FIGURE 6. INDOOR AIR SAMPLER WITH ACOUSTIC ENCLOSURE

vacuum air and cooling air can be discharged into the same chamber. It was necessary, therefore, to provide two inlet chambers and one outlet chamber. The chambers will be referred to as the motor cooling air inlet chamber, the vacuum air inlet chamber, and the combined exhaust chamber. The principal requirement for the chambers was that the air passages be large enough that they would not introduce a significant flow restriction. This design goal was balanced by the acoustic goals since smaller passages would give better sound attenuation. The combined exhaust chamber air is vented through a 4-inch dryer hose which is necessary to carry the hot air away from the box (and out of the room) to prevent recirculation to the sampler and the cooling air inlet. The impact of this exhaust air flow on air flows within a typical residence is discussed in Section 5.

Construction and Materials of the Acoustic Enclosure

As shown in Figure 6, the enclosure base is 18 x 27 inches and the box, without the inlet, is 37 inches tall (total height with inlet is 71 inches). The enclosure frame is made from two 1/2-inch panels of plywood bonded with rubber-base Pliobond© adhesive. Two-piece construction is used to decouple the walls acoustically. The plywood is easily worked and provides a rigid, massive wall which has good noise attenuation properties compared on a weight basis with other materials such as sheet metal. The inside of one entire side of the box is accessible through a removable cover which is secured with latches. Inside, a smaller cover seals the vacuum chambers. All gaskets around the edges of the cover are cut from 1/4-in inert silicone rubber. Box seams are sealed with a latex caulk, which was also selected on the basis of being inert.

The glass-fiber panels are secured with screws and washers wherever necessary. The air flow paths are indicated in Figure 6. One plywood baffle serves to deflect the initial air blast from the motor so it does not impinge directly on the glass fiber.

A list of all materials and their uses in construction of the box is given in Table 2. The entire weight of the sampler constructed using these materials is 67 kg.

TABLE 2. MATERIALS USED IN CONSTRUCTION OF INDOOR AIR SAMPLER

Material	Use
Plywood	Outer shell
Pliobond©	To bond plywood laminate
Semi-rigid glass fiber board	Acoustic insulation
Silicone rubber	Gasket material
Latex caulk	To seal box joints
Stainless steel	Baffle supports
3-M plastic film	Insulation protective cover
Galvanized iron furnace duct	Outlet
Galvanized steel electric service	Electric supply
Duct tape	Used as quick fix seal around motor cooling air inlet

PORTABILITY

A design objective has been to keep the sampler as lightweight and compact as possible consistent with other requirements. Our initial design incorporates all components into the same enclosure with the inlet separable from the motor housing. It does not appear to us that the weight of the device can be significantly reduced without adversely affecting its acoustic acceptability -- which we believe to be a more important criterion.

MAINTENANCE AND CALIBRATION

Components for construction of the indoor sampling system have been selected based on their reliability and requirement of minimal maintenance. The most critical component is, of course, the pump or blower. Consideration of service life, failure frequency, and required maintenance (e.g., brush changes), has led

to selection of the motor used (Amtex by-pass vacuum motor 116100-00 available from Ametek, Lamb Electric Div., 627 Lake Street, Kent OH 44240).

Application to indoor air pollutant measurements requires accurate (±5 to 10 percent) calibration of the sampler flow rate. In the sampler design, provision has been made for multipoint calibration of sampler flow rate over the range that includes the flow rate to be used for indoor air measurements. The device used for this calibration should be an orifice similar to that used for standard hi-vol samplers. Such a device can also be employed for single point quality control flow checks.

SECTION 5

RESULTS AND DISCUSSION

This section summarizes the results obtained in the testing of the performance of the PM-10 inlet, which is described in more detail in Appendix A. Also presented below are the results of the testing of the acoustical performance of the sampler and of the temperature characteristics of the enclosure so designed.

PM-10 INLET TESTING

Wind tunnel testing was performed to determine the fractionation characteristics at a wind speed of 2 km/h with a range of monodispersed liquid aerosol sizes from 5.0 to 20.0 μm aerodynamic diameter and with 20 μm aerodynamic diameter solid particles (glass beads). The effects of variations in the wind speed of the air passing the inlet, flow rate, uniformity of sample on the collection fiber, and angles of attack of the air flow vector were investigated. Tests performed at speeds of 1, 2, and 4 km/h, using 9.7 μm particles, indicate that there is no significant difference in the penetration of these particles through the inlet at these wind speeds. Details of the test methodology and results are presented in Appendix A. A summary of the testing results is presented here.

The basic performance curve of the sampler, Figure 7, shows the penetration as a function of particle size for a wind speed of 2 km/h. Each data point is the average of at least three replicates at each particle size (see Appendix A). Interpolation of the curve shows the cut point to be 10.0 μm aerodynamic diameter. The slope of the curve can be represented by the geometric standard deviation of effectiveness values, s_g, which, for discrete values is:

$$\ln^2 s_g = (1/n) \sum_{i=1}^{n} (\ln D_i - \ln D_g)^2,$$

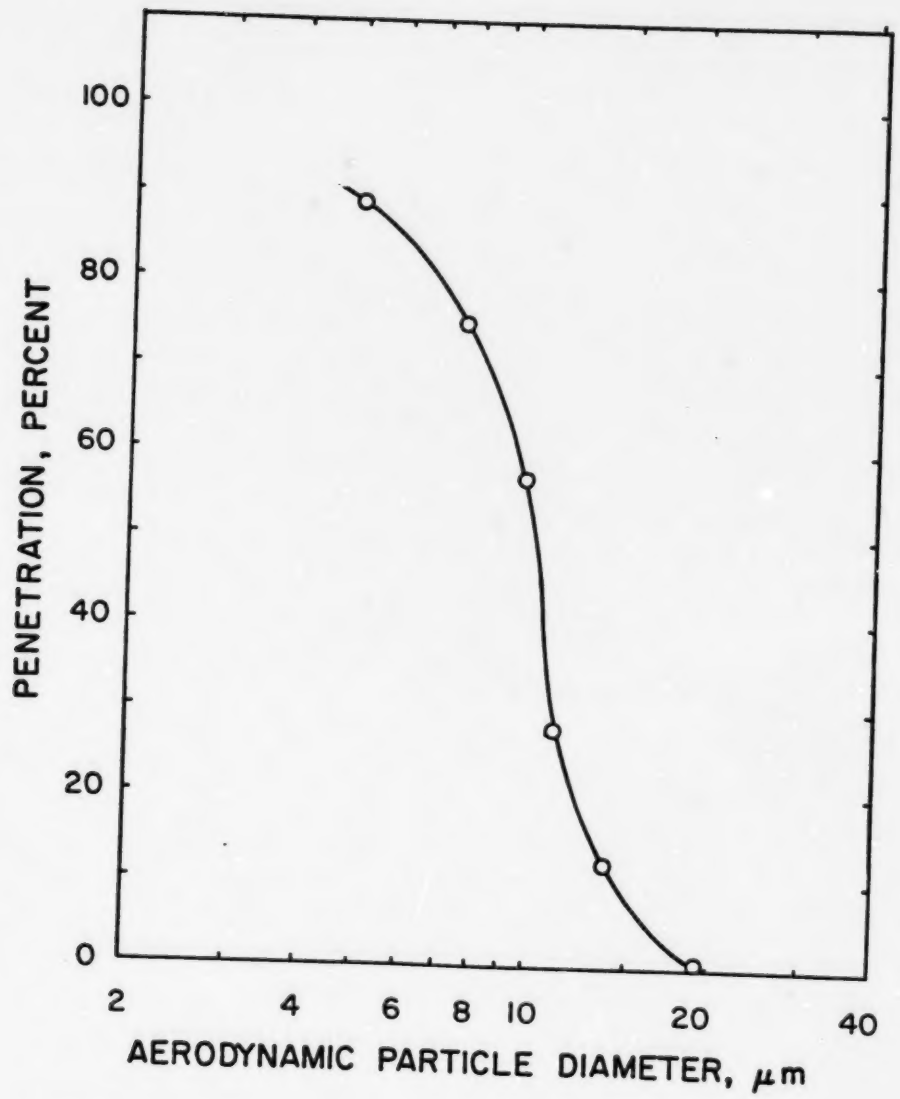


FIGURE 7. PENETRATION CURVE OF PM-10 TWO-STAGE INDOOR INLET (Wind Speed = 2 km/h, Sampling Rate = 240 l/min)

where

n = number of intervals

D_g = geometric mean

$$\ln D_g = \frac{1}{n} \sum_{i=1}^{n} \ln D_i .$$

The parameter s_g was computed by subdividing the curve of Figure 7 into 10 equal penetration increments and taking D_i as the size corresponding to the interval midpoint. The results of this procedure yield a slope, s_g, of 1.51. This value is within the acceptable range for the performance of inertial particle separators, whose ideal performance would be reflected in a value of 1.0 for this parameter.

Tests to determine the influence of air stream angle of attack were conducted by setting the axis of the inlet at -10°, 0°, and +10° relative to the vertical direction. At a wind speed of 2 km/h the sampling penetration for 9.7 μm diameter particles varied only from 51.2 to 53.9 percent over the range of angles of attack.

The unit was operated at sampling rates of 216, 240, and 264 l/min (7.6, 8.5, and 9.3 cfm) in the wind tunnel with a wind speed of 2 km/h and a particle size of 9.7 μm. The penetration values for the three flow rates were 55.3, 53.9, and 53.5 percent, respectively. These data are typical of those which would be obtained with an inertial impactor wherein the passage of particles decreases with increasing flow rate; however, the small variation of penetration suggests that changes in sampling rate of up to ±15 percent will alter the cut point of the inlet by less than 5 percent.

Tests were conducted to determine the uniformity of deposits on the sampling filter. The system was used to collect 10.2 μm particles at a wind speed of 2 km/h and, subsequently, small subsamples were punched from the sampling filter. The pooled standard deviation of 1.8 percent of the mean concentration is on the same order as the analytical reproducibility of most chemical quantification approaches; hence, this level of uniformity is within appropriate bounds.

Tests with solid particles (glass beads) show that the two-stage system performs well. The maximum permissible net solid particle carryover for outdoor

samplers suggested by EPA is 5 percent. For this system the observed solid particle carryover was 2.0 percent.

ACOUSTICAL PERFORMANCE TESTING

The acoustic evaluation of the enclosure with the complete sampler attached was performed with a sound pressure level meter. Since the complete sampler is too tall to fit into Battelle's anechoic chamber, the evaluation was performed in a laboratory room that has walls lined with glass fiber board. The sound level meter calibration was checked prior to the evaluation. The background noise of the room was taken at each octave band and the sampler readings were subsequently corrected for the background noise. The measurements were made five feet from the sampler outlet at a vertical height of five feet. The results are presented in tabular form in Table 3.

TABLE 3. SOUND PRESSURE LEVELS OF INDOOR AIR SAMPLER AT RANGE OF FIVE FEET (Linear dB)

	Octave Band Center Frequency, Hz									
	31.5	63	125	250	500	1000	2000	4000	8000	16,000
Air Sampler	57	58	51	49	40	38	43	43	31	34
Background	55	57	48	37	30	25	<25	<25	<25	<25
Air Sampler Corrected for Background	53	52	48	49	40	38	43	43	31	34

Figure 8 presents the results graphically, compared with the design goal of NC = 35. The air sampler shows an NC = 45. The overall sound pressure level is 48 dBA. Environmental sound is measured with a sound level meter which takes into account the sensitivity of the human ear over the audible spectrum. The weighting network is referred to as the A-weighting network and the values displayed by the meter are referred to as A-weighted levels. The noise criterion

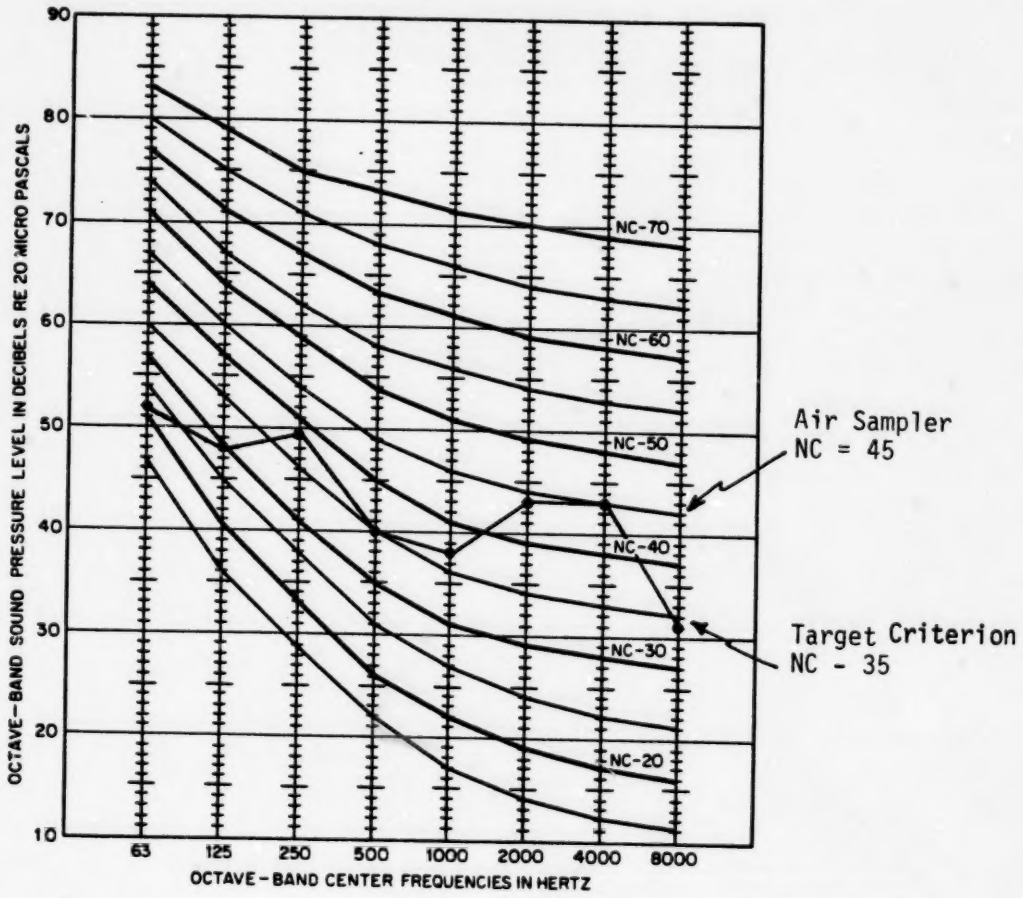


FIGURE 8. NOISE CRITERION (NC) CURVES

and sound pressure levels are both slightly higher than desired. There was an air flow whistle, possibly from a small leak, inside the box. This whistle is probably responsible for the spikes in the noise criterion curve from 2000 to 4000 Hz. Slight design changes may successfully eliminate these spikes, so that the system can meet a noise criterion of 37. Notice that if the two offending points at 2000 and 4000 Hz were lowered, the sampler would already operate at NC = 37.

TEMPERATURE CHARACTERISTICS OF ENCLOSURE

The two issues -- temperatures in the box and air flow through the box -- are closely related. A box completely sealed except for inlet and exhaust would be excellent acoustically, but the motor would overheat. If the air recycles inside the box, the temperature rises to 300 F in less than 15 minutes. Initially, this was the case with the motor cooling air inlet simply connected to the air inlet chamber with the glass fiber tube. It was found to be imperative that this inlet tube be intimately sealed to both the motor and the motor cooling air inlet chamber. This problem discovered during testing was temporarily cured by wrapping the glass fiber tube which connects the air inlet chamber to the blower motor with duct tape. If duct tape is not a suitable solution, this motor cooling inlet seal will need redesign.

A second air flow issue was the vibration isolation gasket, which supports the motor and also seals the vacuum chamber from the exhaust chamber (another possible path for hot air recirculation). The gasket initially leaked excessively, which reduced the pressure drop required for the sampler to perform properly. The silicone rubber gasket originally rested directly on the plywood with only the weight of the motor to seal the contact. A quick fix, which achieved an excellent seal, was to replace the gasket with latex caulk.

Figure 9 shows the temperature characteristics of the box after the above flow problems were addressed. The temperatures were recorded with thermocouples placed in the motor vacuum outlet, inside the motor housing, and in the exhaust chamber just prior to the outlet baffles. As can be seen, the motor is operating

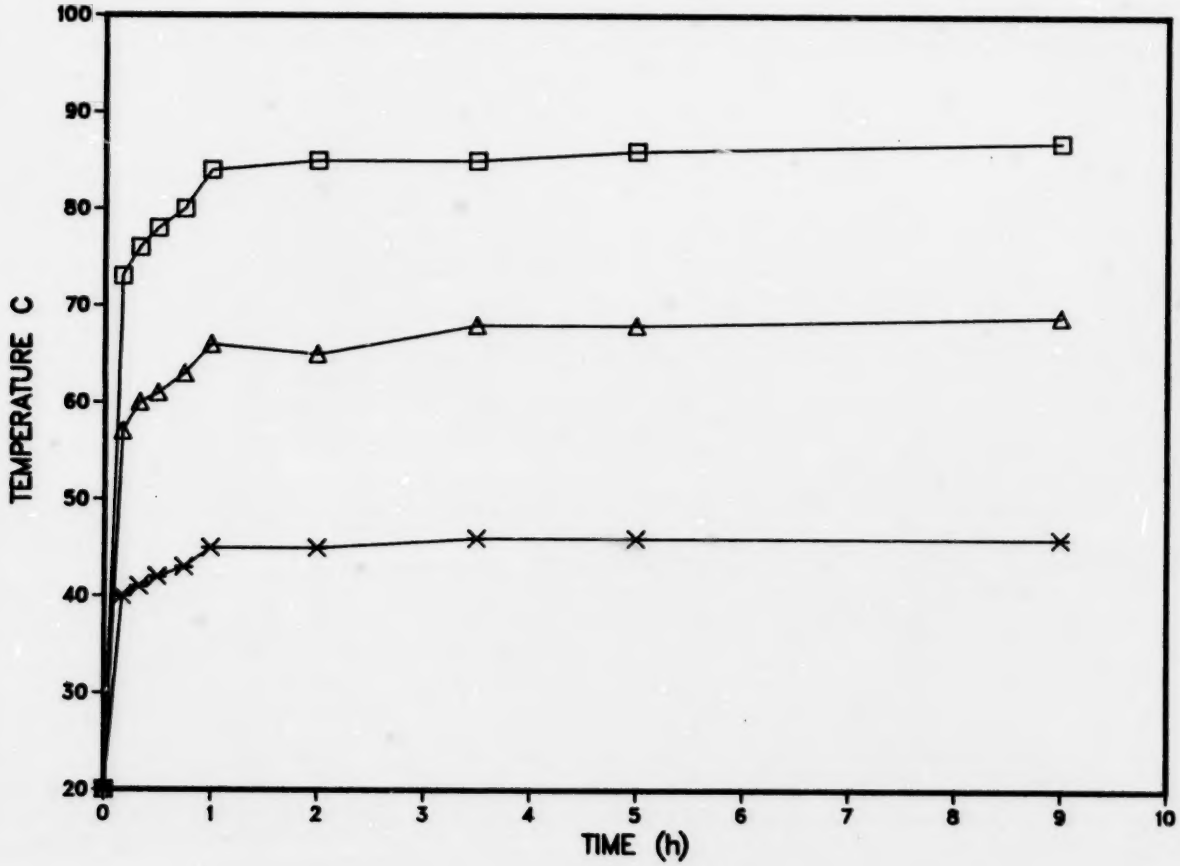


FIGURE 9. TEMPERATURES OF THE SAMPLER ENCLOSURE MEASURED INSIDE THE OUTLET BAFFLES (□), INSIDE THE MOTOR HOUSING (△), AND INSIDE THE MOTOR OUTLET NOZZLE (X)

well below the temperature limit of its Class A winding insulation and should therefore experience a reasonable life, limited by the commutator brushes.

The temperature in the exhaust baffles represents that of the air exhausted by the sampler. Clearly, one would not wish to inject 85 C air into the residence except, perhaps, during winter months. If one exhausts the air outdoors, one has an impact on the overall exchange rate of the house. To estimate the magnitude of the impact, consider a 1500 ft^2 home, with an overall exchange of 0.5 hr^{-1}, which would be characteristic of an energy efficient, or "tight" structure[14]. This represents a total flow rate of 170 m^3/hr or approximately twelve times the sampling rate of the indoor air sampler. This modest perturbation of the overall air-exchange rate seems to us to be preferable to locating the exhaust indoors, which could result in multiple passes of air through the vent.

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APPENDIX A

PM-10 INLET TESTING

Sampler testing was conducted in an aerosol wind tunnel, which has a basic cross section of 0.60 m x 0.60 m with an expanded test section of 1.07 m x 1.07 m. Aerosol is introduced at the tunnel entrance and is subjected to the large-scale eddies created by a mixing baffle which, in turn, produces a uniform aerosol concentration profile across the central 2/3 of the tunnel. The aerosol is then drawn through a grid which reduces the scale of turbulence and into the test section where samples of aerosol are alternately collected with the test inlet and an isokinetic probe.

Aerosol sampling penetration, P, of the test inlet is based upon:

$$P = \frac{C_{inlet}}{C_{iso}}$$

where

C_{inlet} = aerosol concentration in wind tunnel calculated from material collected on the inlet after filter

C_{iso} = aerosol concentration calculated from use of the isokinetic probe.

At each test condition (wind speed, particle size, flow rate, and sampler orientation) at least three replicate samples were collected with each device.

In tests with liquid aerosols, the particles were generated with a vibrating jet atomizer[1] from a solution of oleic acid and sodium fluorescein dissolved in ethanol. After evaporation of the ethanol, the residual oleic acid droplets provide a stable (nonvolatile) aerosol which is easily quantified. Particle size was measured microscopically from droplets

collected on treated glass slides[2]. Equivalent aerodynamic diameter, D_a, of the droplets was calculated from:

$$D_a = (sg)^{1/2} D_p$$

where

D_a = aerodynamic diameter
sg = specific gravity of oleic acid
D_p = actual droplet size.

Mass of aerosol collected on either the after-filter of the test inlet or in the filter of the isokinetic probe was determined fluorimetrically. The sodium fluorescein tag was extracted from the filters with ethanol and the resulting solutions were analyzed with a Turner Model 111 Fluorimeter (GK Turner Assoc., Palo Alto CA).

With respect to the effect of wind speed on sampler performance, the inlet was used to sample a 9.7 μm aerosol at wind speeds of 1, 2, and 4 km/h. The results, Table A-1, indicate a variation of only 53.6 to 55.3 percent in the sampling performance.

TABLE A-1. INFLUENCE OF WIND SPEED UPON SAMPLING PENETRATION
Particle Size = 9.7 μm, Sampling Rate = 240 l/min (8.5 cfm)

Wind Speed, km/h	Number of Tests	Mean Penetration, %	Standard Deviation, %
1	3	55.3	0.265
2	6	53.9	1.238
4	4	53.6	4.592

This suggests that the inlet will not be affected by variations in indoor air currents.

Since the air flow vectors may not always lie in the horizontal plane during field usage of the sampler, it is important that the performance of an inlet is not highly sensitive to air stream angle of attack. To simulate this phenomenon, the inlet was operated in the tunnel with the sampler axis oriented vertically and inclined +10° into the air stream, Table A-2. For these tests, the particle size was set at 9.7 μm and the wind speed at 2 km/h. Since the range of mean penetration values is only from 51.2 to 53.9 percent, the results indicate there is little variation of penetration with the angles of attack of the air stream for the range of test conditions.

With respect to tests to determine the influence of flow rate on the performance of the sampler, the system was operated in the wind tunnel at a speed of 2 km/h and sampled 9.7 μm oleic acid particles. For flow rates of 216, 240, and 264 l/min, the penetration values were 55.3, 53.9, and 53.5 percent, respectively, Table A-3. Thus, the performance is not substantially affected by off-design operation.

Frequently, microchemical analyses are conducted on the sampling filters. In these analyses, only a small part of the filter may be used for the analysis. For reliability of data it is desirable that the sample density be uniform across the filter surface. To check this aspect of the sampling inlet performance, a set of three tests was conducted to determine the uniformity of deposits of 10.2 μm aerodynamic diameter particles. The sampler was operated at a flow rate of 240 l/min in a wind speed of 2 km/h. Subsamples of 13.5 mm diameter were punched from the 90 mm exposed diameter of each sampling filter in the array shown in Table A-4. Data on the mass of fluorescein collected on each filter were normalized to give an average of 1.000 unit. Results, Table A-4, give the mass of fluorescein on each subsample on the normalized basis. Visual inspection of the data shows there are no gross variations of surface density of deposits. Pooled standard deviation of the ten subsamples for the three filters is 0.0175.

TABLE A-2. EFFECT OF SAMPLER ORIENTATION RELATIVE TO THE AIR FLOW VELOCITY VECTOR (Particle Size = 9.7 μm, Wind Speed = 2 km/h, Sampling Rate = 240 l/min)

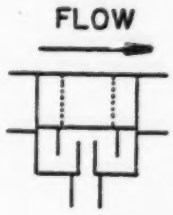
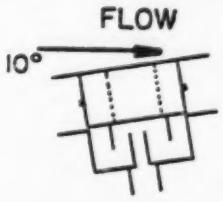
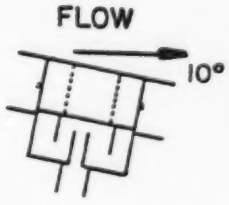
Sampler Orientation	Number of Tests	Mean Penetration, Percent	Standard Deviation, Percent
	6	53.9	1.238
	4	52.5	0.523
	4	51.2	1.842

TABLE A-3. INFLUENCE OF FLOW RATE UPON SAMPLING PENETRATION (Particle Size = 9.7 μm, Wind Speed = 2 km/h, Sampling Rate = 240 l/min)

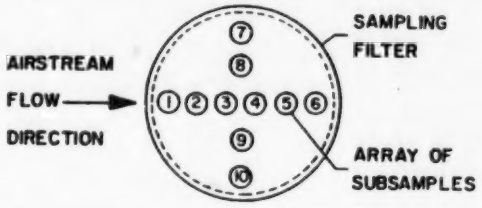
Sampler Flow Rate, l/min	Number of Tests	Mean Penetration, %	Standard Deviation, %
216	3	55.3	0.265
240	6	53.9	1.238
264	4	53.5	2.118

Solid Aerosols

With respect to results with solid particles, the difference between the penetration of solid and liquid 20 μm aerodynamic diameter aerosols was 2.0 percent, Table A-5. This difference between liquid and solid aerosols is small in comparison with corresponding data for many other sampling inlets[3] and is well within the limitation of 5 percent suggested by EPA.[4]

Solid particles were prepared by fractionating a broad distribution of glass beads in order to obtain a narrow size cut. Size distribution of the beads was obtained from use of a Coulter counter (Coulter Electronics, Inc., Hialeah FL) and the resulting volume median diameter was converted to aerodynamic diameter. The distribution of bead sizes is approximately lognormal with a geometric standard deviation of 1.24 and an equivalent volume median aerodynamic diameter of 20 μm. For wind tunnel tests, the beads were dispersed with an air blast aerosolization system and passed through a Kr-85 electrical charge neutralizer before being released into the tunnel inlet. Beads collected on the filters of the isokinetic probe and the test inlet were quantified by gravimetric analysis. Results of solid particle tests are reported in Table A-5 in terms of aerosol penetration, P.

TABLE A-4. UNIFORMITY OF DEPOSITS ON SAMPLING FILTERS (Particle Size = 10.2 μm, Wind Speed = 2 km/h, Sampling Rate = 240 l/min)



Subsample Number	Test 1	Test 2	Test 3	Average	Standard Deviation
1	1.019	1.014	1.005	1.013	0.0071
2	0.973	0.976	1.010	0.986	0.0206
3	0.973	0.999	1.007	0.993	0.0178
4	1.015	0.995	0.973	0.994	0.0210
5	0.981	1.010	0.987	0.993	0.0153
6	1.013	1.003	1.028	1.015	0.0126
7	1.044	0.995	0.995	1.011	0.0283
8	1.013	1.020	0.987	1.007	0.0174
9	0.981	0.999	1.011	0.997	0.0151
10	0.988	0.988	0.999	0.992	0.0064
Average	1.000	1.000	1.000		
Standard Deviation	0.0240	0.0128	0.0155	Pooled std. dev. of 10 subsamples = 0.0175	

TABLE A-5. PENETRATION OF 20 μm GLASS BEAD AEROSOLS (Wind Speed = 2 km/h, Sampling Rate = 240 l/min)

Aerosol	Number of Tests	Mean Penetration, %	Standard Deviation, %
Glass beads	3	2.3	0.376
Liquid aerosol	3	0.3	0.0

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